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STUDIES OF ANISOTROPIC PERMEABILITY WITH APPLICATIONS TO WATER REMOVAL IN FIBROUS WEBS

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ABSTRACT

An extensive set of data for in-plane and transverse permeability has been obtained. We focus on recent results for hardwood and softwood kraft pulps which are consistent with measurements in other pulp types. Anisotropic permeability data are discussed in terms of practical implications and theoretical considerations such as pore structure.

The new data give insight into two-dimensional flows which may occur in practical papermaking and nonwovens processes. The observed tendency for fiber networks to have high in-plane permeabilities is especially relevant in water removal processes. For example, in-plane flows can reduce the water removal capacity of a press. Saturated permeability data are also directly correlated with impulse drying performance. As a measure of water removal performance, saturated permeability data are much more relevant than freeness data.

A variety of factors can influence the saturated transverse or in-plane permeability of a fibrous network. We consider the effects of compression, fines content, basis weight, yield, and different disintegration and refining methods. In addition, the effects of hornification from drying and partial hornification from wet pressing were quantified. Partial water removal by pressing results in some hornification, increasing the permeability of the resaturated sheet. The permeability of a dried and resaturated sheet increased more than the permeability of a sheet formed from dried and reslushed fibers.

KEYWORDS

Permeability, flow through porous media, anisotropy, wet pressing, impulse drying, recycled fibers, hornification.

BACKGROUND

Darcian Permeability

Paper permeability is commonly expressed in terms of gas flow rates through a sheet. This practice is useful for comparing similar sheets, but does not truly characterize the interaction of flowing fluid with the porous structure and provides no direct information about flow in a wet sheet. The standard engineering definition of permeability provides a more useful parameter, though one less easily measured. The standard definition is based on Darcy's law (1), which, for one-dimensional flow, states that the velocity of fluid flow through a saturated porous medium is directly proportional to the pressure gradient:

$$v = \frac{K}{\mu}\frac{\Delta P}{L} \qquad (1)$$

where v is the superficial velocity (flow rate divided by area), K is the permeability, μ is the fluid viscosity, and ΔP is the pressure drop in the flow direction across a distance L. The units of K are m^2. In Equation (1), the permeability is an empirical proportionality parameter linking fluid velocity to pressure drop and viscosity. For a homogeneous medium, K is not a function of ΔP, sample length, or viscosity, but is an intrinsic parameter describing the flow resistance of the medium. In a compressible medium, permeability will be a strong function of the degree of compression.

Importance of Permeability

Darcian permeability is commonly a fundamental parameter for processes involving fluid flow in fibrous webs (2-5). In nonwovens, for example, the permeability of the fibrous structure affects product behavior in processes such as liquid infiltration, rewet, and wicking, although such flows are also complicated by multiphase phenomena, especially surface tension effects.

In paper manufacturing, permeability can control the amount of water removal possible in a press nip. In impulse drying, a pressing process involving intense heat transfer from a heated roll, permeability is also expected to be of fundamental importance. Not only will permeability control the water removal ability of the impulse-dried sheet, as in standard wet pressing, but permeability will also directly affect the vapor phase that forms in the sheet, with low sheet permeability leading to higher internal vapor pressures and a greater tendency for delamination (sheet rupture due to internal vapor pressure). Details on the role of permeability in impulse drying and related water removal processes are given in (6-8).

Permeability is also of direct importance in drying operations, where it affects vapor flow and liquid flow driven by bulk pressure gradients (9). Permeability of the sheet to vapor can be a limiting factor in high-intensity drying operations (10).

Anisotropic permeability becomes an issue whenever two-dimensional fluid flows are possible in a web. Pressing operations are one example (11-13). Although the flow in a nip is primarily in the transverse direction, some in-plane flow components can exist. This in-plane flow becomes especially important when crushing occurs (14). The small in-plane flows can also contribute to economically significant reductions in water removal, depending on the anisotropic permeability of the sheet (15).

In-plane flows can also be important in blade coating, where a large pressure gradient in the machine direction exists under the blade (16). Penetration of the coating color can then involve both z-direction and lateral flows. Characterization of the process requires knowledge of the lateral permeability as well as the transverse permeability.

In-plane permeability can also be important in nonwoven products such as diapers and other absorbent products. In the broad area of textiles, measurements of in-plane permeability have been conducted for some time at TRI (17-20). These studies will be mentioned in more detail below.

Factors Affecting Permeability

The permeability behavior of a paper sheet is affected by numerous factors, including refining, yield, fines content, pH, and sheet formation. For example, Carlsson (21,22) and Ellis (23) found that permeability decreased with increased refining; high freeness pulp tends to have high permeability. Gren (24) examined the effect of cooking method and yield, finding in general that an increased kappa number or higher yield resulted in increased permeability to water.

Ellis observed a basis weight effect in which lightweight sheets had a higher permeability than expected. He speculated that this result was due to an end effect due to the roughness of the porous tester plate which supported the sheet.

Another interesting feature observed by Ellis was an effect of consistency during formation. Sheets formed at low consistencies at which little fiber entanglement occurred in the stock tended to have lower permeability than sheets formed at higher consistencies where fiber flocs could form. Based on the figures Ellis presents, it appears that the high consistency sheets may have 2-4 times the permeability of sheets formed at low consistency.

Studies of Anisotropic Permeability

While much has been published about the z-direction or transverse permeability of paper (21-32), measurements of the lateral permeability components and their relation to transverse permeability have not been available in the literature. For lack of better information, those who have dealt with two-dimensional flows in paper have tended to assume that the permeability of paper was uniform in all directions (1,4,33), even though paper is an obviously anisotropic material.

This lack of data is surprising, since measurements of anisotropic permeability have been made in felts, textiles, rocks, and other porous materials, although fibrous materials in general have been neglected (see [34] for a broad review of permeability measurements in fibrous materials).

Relevant work, however, has been done by Back (35,36), who examined multidimensional capillary flows in paper. By observing the way in which a drop of fluid spreads out in a sheet of paper, information about anisotropy in the sheet can be obtained. He found that the capillary penetration velocity for most papers is 5-15% larger in the machine direction than in the cross-direction, and concluded that ratios of in-plane pore size to transverse pore size ranged from about 3 to 100. A similar study was conducted by Ernst (37), who measured penetration of a non-wetting fluid in all three directions of several paper types to estimate effective pore sizes. His results showed that in-plane pores were generally 5-20 times greater than those in the thickness direction.

Caution must be used in interpreting the results of capillary flow data. Even if capillary flows can be used to determine effective pore size, these studies do not directly address the issue of anisotropic permeability, for capillary flow is affected by both the intrinsic Darcian permeability of the sheet as well as the directional pore size distribution. No quantitative conclusions about permeability can be safely deduced from such experiments unless detailed information about the directional pore size distribution is available.

Peterson (38) examined the two-dimensional permeability of thick, nylon fiber mats with fibers oriented in the horizontal plane. He found the lateral permeability was 25-30% higher than the transverse permeability. Mat porosities ranged from 0.84 to 0.97. While a thick nylon mat is not an accurate model of paper, the study provides an important reference point.

Several relevant studies with textiles have been conducted at TRI (Textile Research Institute in Princeton, NJ). Adams et al. (17-19) and Miller et al. (20) developed techniques to measure the in-plane permeability of textiles. In one method, in-plane flow was obtained by placing a dry textile fragment between two glass plates with a circular opening in the center of one plate for fluid injection. A viscous epoxy resin was injected at constant pressure into the textile, forcing the fluid radially outward. The size and shape of the wetted region were observed and recorded in time. The advantage of this technique is that the permeability in two orthogonal directions in the plane can be obtained simultaneously. The high permeabilities of the textiles apparently precluded difficulties with channeling in the permeability measurements. While the focus of the work at TRI was on in-plane flow, Adams (39) reported four transverse permeability measurements in textile samples for which lateral permeability measurements had also been made. The ratio of lateral to transverse permeabilities ranged from 2 to 5.

Studies of anisotropic permeability in felts have been conducted by a number of researchers. Kershaw (40), for example, measured flow in three directions in a variety of press felts. He found the transverse permeability to be higher than the lateral permeabilities. Significant differences in press performance for felts with similar transverse permeabilities but dissimilar lateral permeabilities suggested that two-dimensional flow in felts plays an important role in wet pressing. Chevalier (41) has also reported measurements for directional permeability in felts, finding in-plane permeabilities on the order of 2-3 times the transverse permeability.

To explore basic issues about the anisotropic permeability of paper, a project was launched at The Institute of Paper Chemistry in 1987. Early results have been published by Lindsay (42,43), who measured the transverse, cross-direction, and machine-direction permeability components in several paper samples. In the few samples which were examined, the ratio of average lateral to transverse permeability ranged from roughly 2 to 10, which was larger than predicted by simple models of flow over oriented cylindrical rods (44,45), but consistent with data from Adams (39) for textiles, where ratios of 2 to 5 were reported.

The ratio of machine-direction to cross-direction permeability was also obtained in several paper samples (46), with values generally in the range of 1 to 2 and frequently in the range of 1.1 to 1.3. In a related study by Horstmann et al. at IPST (47), a new experimental method to characterize edge penetration in photographic papers was used to provide information on anisotropic in-plane permeability. Measurements in five similar samples of uncompressed photographic paper again showed MD-CD permeability ratios in the range of 1.1 to 1.3. Transverse permeability was not measured.

EXPERIMENTAL APPROACH

Equipment

Lateral permeability. The basic experimental procedure has been previously described (42,43,48). Figure 1 shows the apparatus for lateral permeability measurements in saturated sheets. A modified Carver press with an air bag assembly allows paper to be pressed between two platens. The lower platen has an 0.56-cm hole at the center through which fluid is injected. Fluid is driven into the port by regulated compressed air above the fluid meniscus in the line. Flow rates are determined by tracking the fluid meniscus in the translucent tubing.

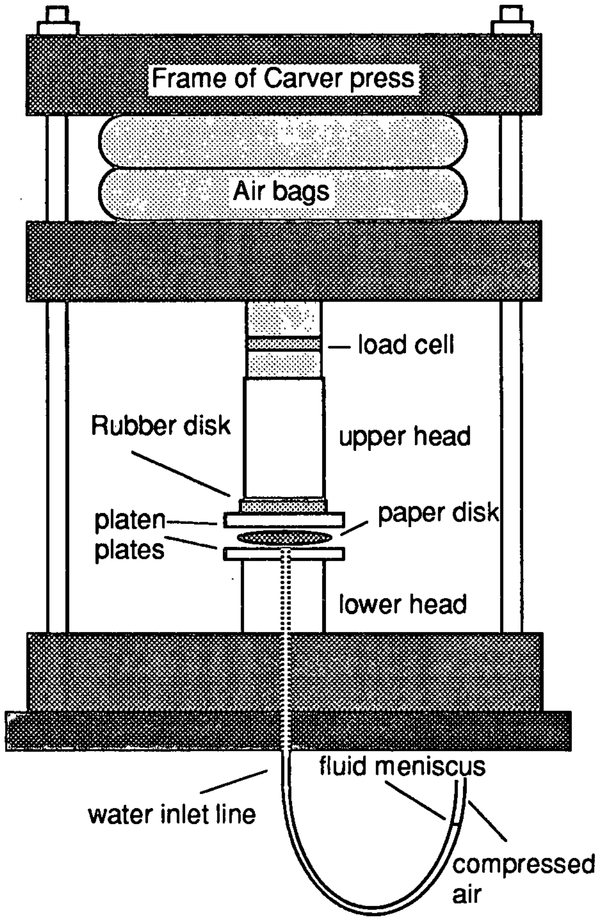

Figure 1. Schematic of the lateral permeability setup.

After a saturated paper disk is placed between the two platens, pressure is applied to provide a seal between the paper surfaces and the platens. Fluid in the tubing line is then pneumatically driven into the paper. The fluid flowing into the injection port enters the paper and is forced to flow radially outward through the paper itself. If the applied load is uniform and the sheet itself is uniform in thickness, then channeling flow between the sheet and the platens is avoided. This was verified by observing the location of dyed fluid injected into sheets.

The thickness of the paper disk during lateral permeability measurements was measured with a set of linear variable displacement transducers (LVDT's) embedded at 120° intervals around the edge of the lower platen, with sensor armatures mounted on the upper platen.

The average lateral permeability is expressed in terms of measured parameters:

$$K_r \equiv \frac{K_x+K_y}{2} = \frac{Q\,\mu\,\ln(R_o/R_i)}{2\pi\,L\,\Delta P}, \qquad (2)$$

where Q is the volumetric flow rate based on the motion of the meniscus in the supply tubing, R_o is the outer radius of the sheet, R_i is the radius of the injection port, L is the sheet thickness, and ΔP is the pressure drop from the injection port to the edge of the sheet. Details of this solution are given in (47). While Equation 2 is based on a simplification of the flow problem, numerical analysis has indicated that it can be applied with reasonable accuracy (46).

Transverse permeability. The equipment used to measure transverse permeability also uses the Carver press frame and is shown in Figure 2. The basic features of the equipment have been previously reported (42,43,46).

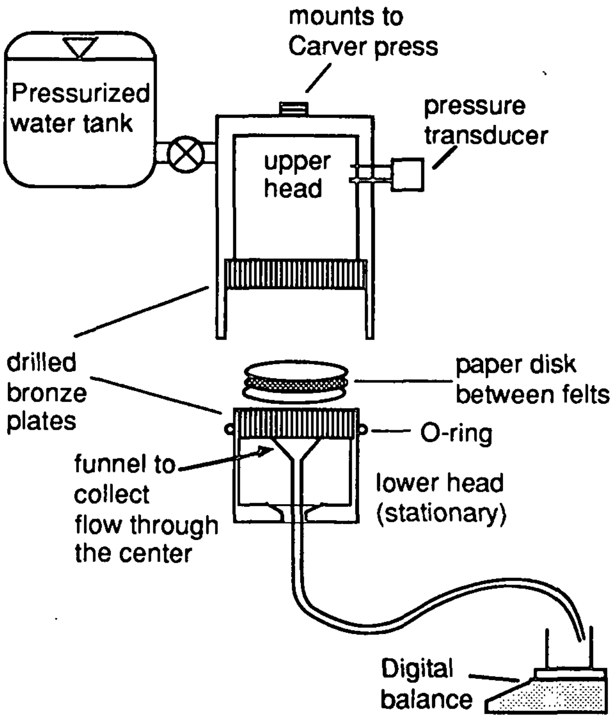

Figure 2. Schematic of the water flow system for transverse permeability measurements.

In making transverse permeability measurements, a saturated paper disk is compressed between two wet felts. The felts are in contact with finely drilled bronze plates that transmit mechanical pressure while allowing water to flow through. Carbon paper imprints taken under load confirmed that the felts were adequate in generating a uniform load across the paper.

To eliminate problems with leakage around the edge of the paper, only the flow through the central region (comprising 23% of the area of the paper disk) was collected and measured. This fluid entered a funnel which led the fluid through plastic tubing to a graduated cylinder below the Carver press assembly. Others have used compression rings around the edge of the sample to prevent edge flows. The present method allows compressibility data to be obtained while measuring permeability (with compression rings, the mechanical load experienced by the bulk of the sheet is unknown) and makes it easier to have uniform pressure across a sheet.

Sheet thickness was obtained using a Kaman eddy-current transducer (ECT). By measuring the position of the upper head while compressing two felts alone and then while compressing the two felts plus paper, the thickness of the sheet could be obtained from the difference. Cubic regression of the thickness-versus-load data was done for the felts before and after each run. The accuracy of the thickness measurement is estimated to be ± 9 µm (0.35 mils). Further details are given in (43). Given the inherent uncertainties in defining paper thickness, this error is acceptable.

In transverse permeability measurements, water passes through the central region of the paper and felts with a known pressure drop. The permeability is given by:

$$K_z = \frac{L}{\frac{A_{flow}\,\Delta P}{Q\,\mu} - R_f}, \qquad (3)$$

where A_{flow} is the cross-sectional area of the flow collection region (23% of the sheet area) and R_f is the inherent resistance of the felts and flow system. R_f was usually of little importance since the paper resistance was so much greater than the resistance of the felts or other components of the flow system.

The use of press felts to distribute load and permit flow offers several advantages over rigid media, such as sintered metal plates, which offset the disadvantage of having to calibrate felt thickness as a function of load. The compressibility of felts makes it much easier to apply a uniform mechanical load, even when nonuniformities exist in the sample. The low flow resistance and high load uniformity of felts are not easily matched with available rigid media.

Porosity

Porosity, ε, or void fraction (volume fraction of water), is obtained from the sheet thickness and dry weight:

$$\varepsilon = 1 - \frac{m}{A\,L\,\rho_c} \qquad (4)$$

where m is the oven-dry mass of the sheet, A is the planar area, and ρ_c is the density of cellulose, 1,550 kg/m^3. This standard engineering definition of porosity is dimensionless, whereas a variety of industrial tests of paper properties yield 'porosity' values in terms of dimensional quantities such as flow rates of air.

Sheet Preparation

Most of the sheets in this study were formed from two pulp types, a bleached southern softwood kraft and bleached southern hardwood kraft. In addition, some tests were done with unbleached southern softwood kraft, unbleached northern softwood kraft, and bleached northern hardwood kraft. Paper samples were formed on British handsheet molds or, in the case of the unbleached kraft pulps only, as samples cut from a wet web produced on a flow spreader. For handsheets, stock preparation was done according to TAPPI procedures, except that some pulp samples were over disintegrated (150,000 revolutions instead of the standard 50,000). Most pulp was unrefined, although light refining with a PFI mill was done for several samples to vary freeness.

Wet handsheets were prepared from pulp samples using standard TAPPI method T205 om-88 (49) with several exceptions. The newly formed handsheets were only lightly pressed (70 kPa for 1 minute instead of 345 kPa for 5 minutes) to maintain high saturation (20-25% solids). Some sheets at higher solids levels (ca. 50%) were obtained by pressing at 345 kPa for 3 minutes.

A wide variety of handsheets were tested. Most of the work was done with bleached kraft pulps, with the various classes listed in Table 1. Bleached pulp types included southern softwood (SSW), southern hardwood (SHW), and northern hardwood (NHW). Mechanical treatments included Tappi standard (S), over-disintegration (OD), and PFI-mill refining in addition to standard disintegration (PFI). Three wires of differing mesh size were used in the British handsheet former; wires 1 and 3 were 150 mesh and wire 2 was 100 mesh. Because earlier work gave some evidence of permeability changes with storage time of pulp, the effect of aging was examined by comparing sheets made with fresh pulp with those made from the same pulp after five weeks of storage in a cold room. Pulp was stored with some added formaldehyde to prevent microbial degradation.

Table 1. Different classes of sheets made from bleached pulp.

Pulp	B. Wt., gsm	Mech. Treat.	Wire	Age	Other
SSW	135	S	1	Fresh	
SSW	270	S	1	Fresh	
SSW	145	S	2	Fresh	
SSW	300	S	2	Fresh	
SHW	135	S	1	Fresh	
SHW	270	S	1	Fresh	
SHW	100	S	2	Fresh	
SHW	200	S	2	Fresh	
SSW	135	OD	1	Fresh	
SSW	270	OD	1	Fresh	
SHW	135	OD	1	Fresh	
SHW	285	OD	1	Fresh	
SSW	135	PFI	1	Fresh	
SSW	270	PFI	1	Fresh	
SHW	135	PFI	1	Fresh	
SHW	270	PFI	1	Fresh	
SSW	135	S	1	Fresh	100% solids
SSW	135	S	1	Fresh	50% solids
NHW	135	S	1	Aged	
SSW	135	S	1		Recycled
SSW	400	S	3	Aged	
SSW	270	S	3	Aged	
SSW	135	S	3	Aged	
SHW	270	S	3	Aged	

In addition to the bleached pulp samples, measurements were also made in several unbleached kraft sheets from both northern and southern softwoods. Two different freeness levels were examined, 550 and 650 CSF, with freeness varied by refining in a Valley beater.

Run Procedures

Transverse permeability. In transverse permeability measurements, 7.6-cm paper disks cut from wet handsheets were placed between two wet felts. The thickness of the felts as a function of load was measured before and after each run. The felt and paper were placed on top of the lower drilled bronze disk, then the hydraulics of the system were used to lower the upper head. A valve was opened to allow deaerated water to fill the upper chamber and to begin flowing through the felts and paper. The air line to the air bag was adjusted to achieve a specified load on the paper, as read from an LCD meter connected to a load cell. An initial mechanical pressure of about 200 kPa was applied. Several readings of flow rate and sheet thickness were made over 2-4 minutes, whereupon the mechanical load was increased and more measurements were made.

As mechanical load was increased, sheet permeability decreased and longer flow sampling times were needed for accurate measurements. Maximum applied pressures were often near 700 kPa.

Lateral permeability. Saturated 7.6-cm disks cut from handsheets were again used and placed on the lower platen containing an injection port. The injection port and injection line were previously filled with fluid. The upper platen was placed on the sheet, guided by two guideposts to ensure that the LVDT armatures were properly centered in the sensor cores. Mechanical pressure was applied through the airbag assembly, beginning with about 200 kPa and gradually increasing to 700 or 800 kPa. At each mechanical load, the distance traveled by the air-liquid meniscus in the injection line was tracked in time to obtain the flow rate. LVDT readings were recorded to give sheet thickness. LVDT's were calibrated daily. Occasional tests checked the pressure uniformity and flow symmetry about the injection port.

RESULTS

A large set of data was collected in this phase of the permeability study. Representative data are presented below. Permeability values are typically plotted against porosity, which is the fractional volume of the sheet occupied by water as defined in Equation 4 above. The porosity range shown depends on the compressibility of the sheet over the applied mechanical pressure interval. The high porosity data points are typically at mechanical pressures of 200 kPa, and the low porosity data were typically obtained near 700 kPa. When sheets were compressed during a transverse permeability run and then later subjected to a lateral permeability test, the first compression cycle caused some permanent deformation, resulting in lower porosities at a given load. However, replicate tests showed that the permeability-porosity relationship was unchanged after undergoing a cycle of compression as long as the sheet was kept saturated.

Anisotropy

Results of the present study confirms the observation in earlier IPST work that in-plane permeability tends to be much greater than transverse permeability. Figures 3 and 4 show typical anisotropy in bleached softwood sheets, with ratios of lateral to transverse permeability on the order of 5-10. Figure 5 shows similar results in hardwood sheets. Figure 6 shows an example of data revealing extremely high anisotropy ratios, with lateral permeability around 40 times as high as transverse permeability. Measurements in handsheets from the bleached northern hardwood sheets also showed high anisotropy, as indicated in Figure 7.

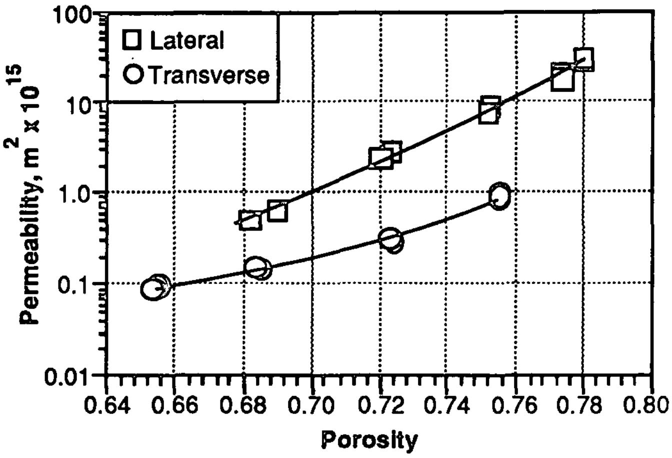

Figure 3. Anisotropy in 300 gsm bleached southern softwood sheets (two separate sheets used), 715 CSF.

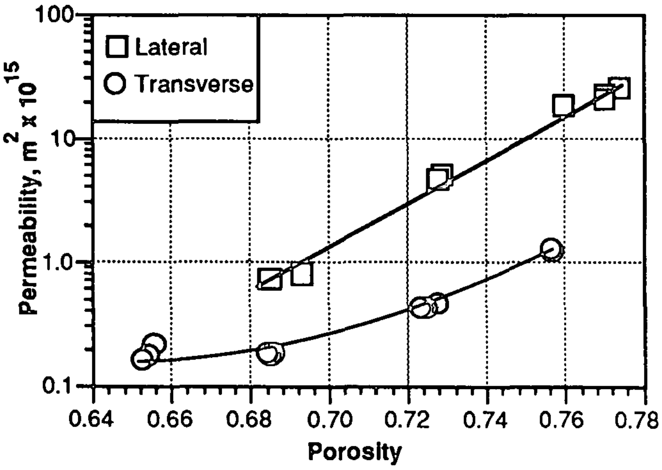

Figure 4. Anisotropy in 270 gsm bleached softwood sheets (two separate sheets used), 715 CSF.

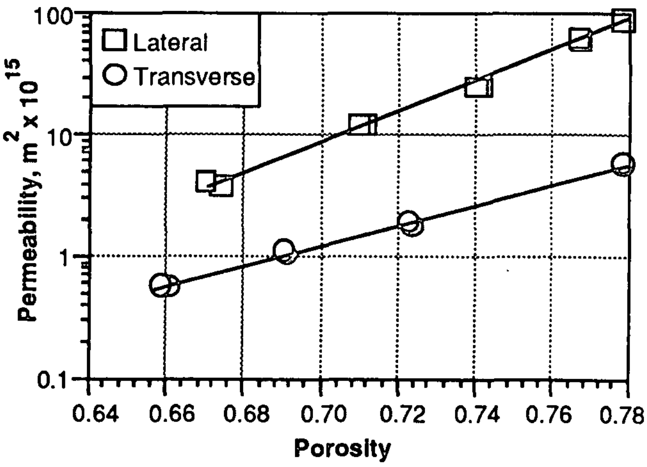

Figure 5. Anisotropy in 270 gsm bleached hardwood sheets (two separate sheets used), 653 CSF.

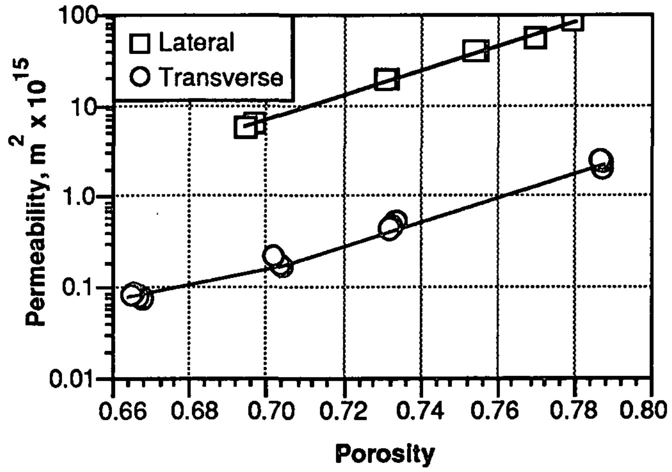

Figure 6. High anisotropy in a 270 gsm bleached hardwood handsheet, 581 CSF.

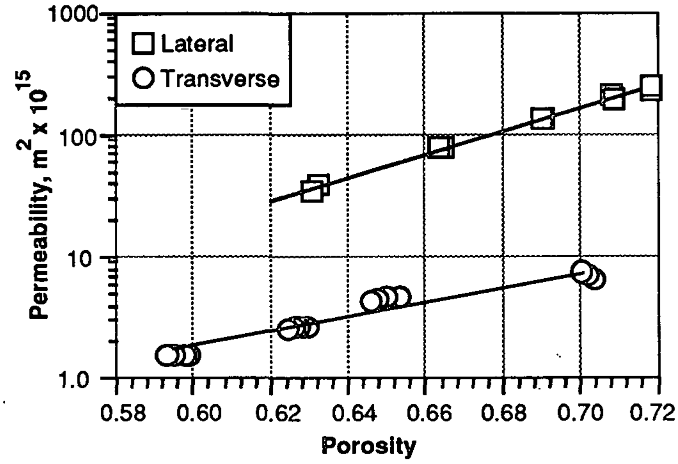

Figure 7. High anisotropy in a bleached northern hardwood pulp, 665 CSF, 135 gsm sheet.

Data for unbleached softwood sheets are given in Figure 8, where anisotropy ratios on the order of 2-4 are found. Early measurements in unbleached softwood from this study also found anisotropy ratios of 2-4. However, much higher anisotropy in unbleached softwood kraft sheets is sometimes observed, as shown in Figure 9. Anisotropy is expected to be affected by details of sheet formation as well as intrinsic fiber properties. The unbleached sheets used in this study were formed on a low-velocity flow spreader that probably imparted a different formation and pore structure than a handsheet former.

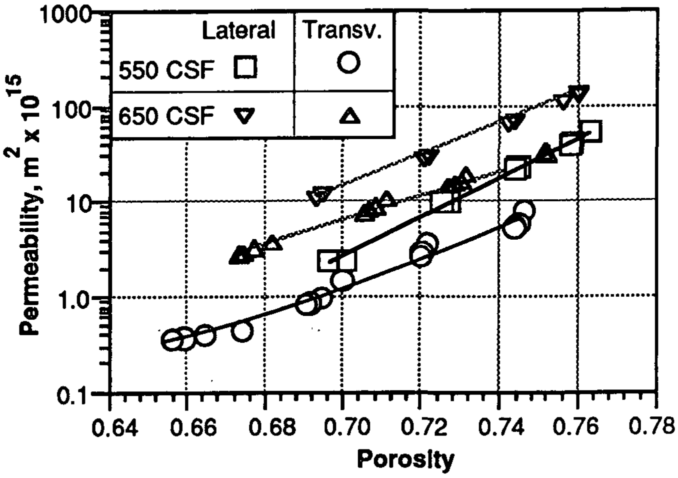

Figure 8. Lateral and transverse permeability measurements in two sheets of unbleached southern softwood kraft at freeness levels of 550 and 650 CSF. Initial solids 41%.

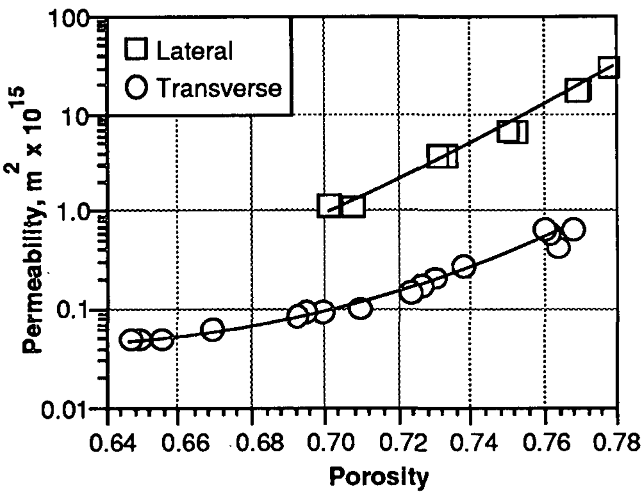

Figure 9. High anisotropy in a 200 gsm unbleached southern softwood handsheet, 650 CSF, 35% solids initially.

High anisotropy has also been observed in unbleached TMP handsheets in previous measurements from this study (43), as shown in Figure 10. Anisotropy ratios (lateral permeability divided by the average in-plane permeability) were often on the order of 10-20 for TMP samples of all basis weights.

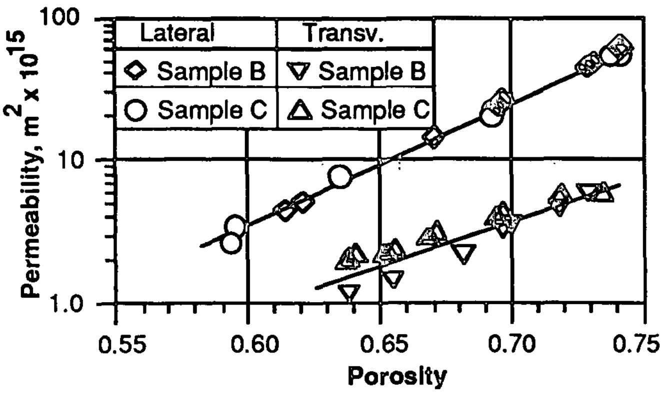

Figure 10. Anisotropic permeability in two sheets of 200-gsm TMP.

The finding of high anisotropy in sheets from various pulp types suggests that the inherent pore structure in a fibrous web such as paper has larger channels in the plane than in the z-direction. This has ramifications for water removal operations in which two-dimensional flow may be possible, as discussed below.

CSF and Permeability

An important result from this study concerns the danger of relying on freeness as a measure of permeability or water removal capability of a sheet. Measurements of CSF are commonly assumed to give information on the water removal properties of a pulp, and this assumption is true, to a degree. For a given pulp type, mechanical treatments which reduce CSF will also usually reduce permeability and thus hinder water removal in pressing and drying operations. However, the relationship between permeability and freeness is not only nonlinear and different for each pulp type; it is also path-dependent, meaning that different treatments to achieve a given freeness level may result in different permeabilities. In other words, CSF may be a poor measure of water removal behavior.

Figure 11 demonstrates the path-dependent relationship between freeness and transverse permeability in 270 gsm bleached southern softwood sheets. (Unless otherwise specified, permeability data presented from this point on refer to transverse permeability.) Over-disintegration (three times the Tappi standard) and PFI refining of the same pulp, initially 715 CSF, resulted in two different freeness values but virtually the same permeability. The difference in freeness between the two treated samples is less than the difference in freeness between the original pulp and the over-disintegrated pulp. The same effect is shown for 135 gsm sheets in Figure 12. Hardwood fibers responded in the same way, as shown in Figure 13.

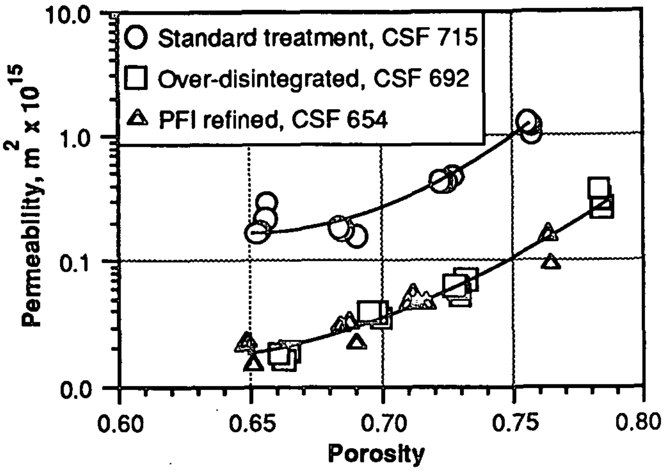

Figure 11. Transverse permeability of bleached softwood sheets, 270 gsm, after various mechanical treatments to the pulp.

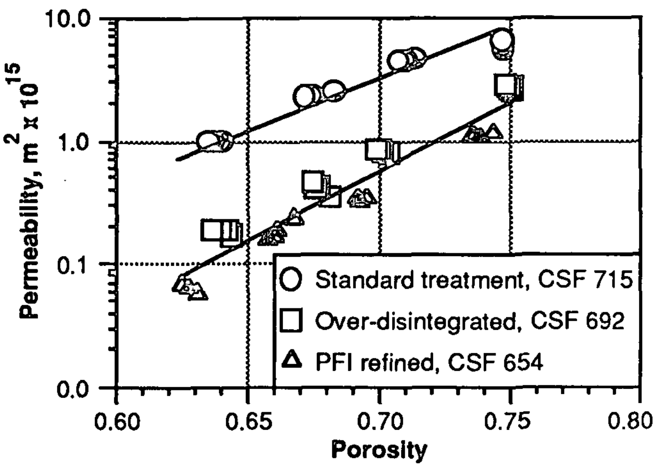

Figure 12. Permeability of bleached softwood sheets, 135 gsm, after mechanical treatments to the pulp.

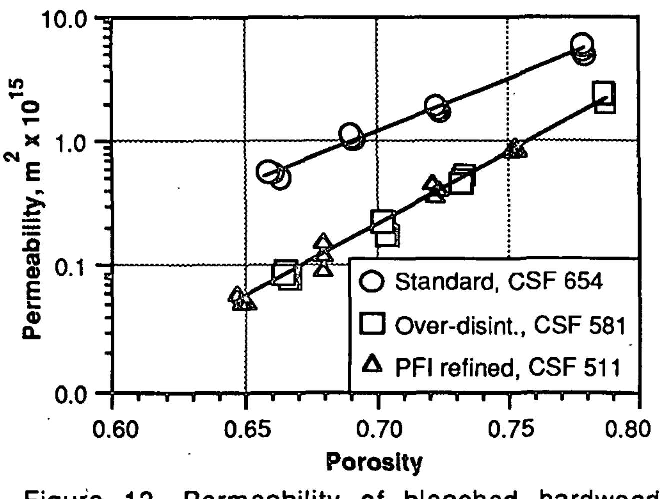

Figure 13. Permeability of bleached hardwood sheets, 270 gsm, after various mechanical treatments to the pulp.

Small changes in freeness may cause large changes in permeability. For example, a reduction in freeness from 700 to 500 may correspond to a permeability change of two orders in magnitude. Permeability appears to be a more sensitive parameter than freeness, in addition to being more useful in describing water removal behavior. Freeness, however, is likely to be more useful than permeability in describing drainage behavior on a wire.

Permeability, CSF, and impulse drying behavior. During this study, we were asked by David Orloff of IPST to examine the permeability of some papers that had given somewhat perplexing behavior during impulse drying. Sheets from two supposedly similar pulps (both unbleached kraft softwood with the same CSF values) had remarkably different behaviors during impulse drying. One dewatered easily, showing remarkable potential in impulse drying. The other delaminated, meaning that internal vapor pressure generated by contact with the hot rolls caused the sheet to blister and even blow apart as it left the nip. Unfortunately, the first pulp type was used in early tests of impulse drying, leading to great enthusiasm for the process (50), while the other pulp type was used in industrial pilot testing, leading to serious apprehensions (51).

These results were perplexing until permeability was measured. The pulp that delaminated easily had a much lower transverse permeability, as shown in Figure 14, although both pulps had the same freeness. The low permeability pulp also had a lower kappa number, so differences in cooking probably contributed to the lower permeability. According to our current understanding of impulse drying physics, a low permeability results in high vapor pressure build-up in the sheet, and the pressurized vapor is not easily vented through the low-permeability web as the sheet leaves the nip. As a result, pressure forces in the sheet can then cause delamination.

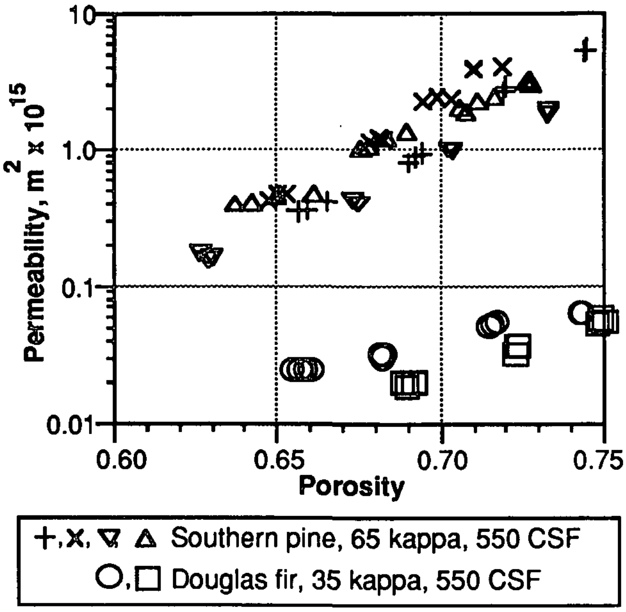

Figure 14. Differences in transverse permeability between two unbleached softwood pulps at the same freeness. Results for several sheets are shown.

The Effect of Water Removal on Permeability

Pressing and drying. While water removal is affected strongly by sheet permeability, the process of water removal also changes the permeability of the sheet even after it is resaturated. We are not referring to the reduction in apparent permeability that occurs when two immiscible phases (water and air) are competing for pores during two-phase flow, but to physical changes in the pore structure of paper that occur as water is removed from some of the pores. This process of "hornification" occurs as capillary and other surface forces close many small pores, partially through bonding between microfibrils as water is removed. The closed pores are no longer open to water, diminishing the swelling capacity of the fiber and reducing its swollen volume and its swollen surface area. As a result, there can be more space between the fibers open to water flow and permeability can increase.

In Figure 15 we show changes in the transverse permeability of saturated 135 gsm bleached softwood sheets which have been conditioned by pressing to 25% or 50% solids or by oven-drying to 100% solids prior to resaturation. In Figure 16 we show similar results in unbleached softwood sheets pressed to different solids levels before resaturation. A permanent change in pore structure is evident as water is progressively removed from the fibers. Partial water removal increases the permeability of the subsequently resaturated sheet. For example, the water removed in the first press may increase the permeability of the sheet when it is resaturated by compression in the second nip, although this may be offset by the increased density of the sheet.

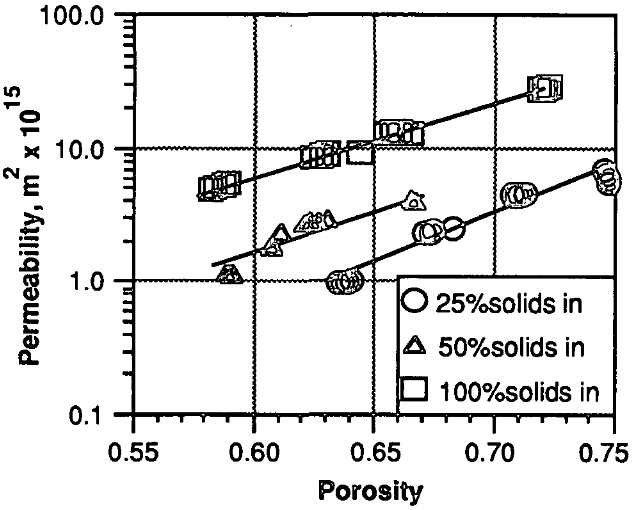

Figure 15. Effect of pressing and drying on the transverse permeability of a 135 gsm bleached softwood sheet.

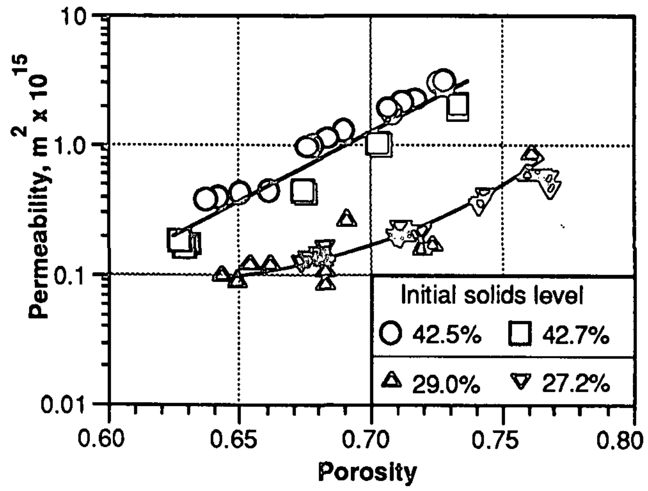

Figure 16. Effect of partial water removal through pressing on the transverse permeability of subsequently resaturated sheets of 200 gsm unbleached southern softwood kraft, 550 CSF.

Hornification and its effect on permeability is well known for recycled fibers (completely dried and reslushed), but the possibility of hornification during wet pressing operations is less well known. Washburn and Buchanan (52) noted that progressive water removal by pressing transforms the paper from a structure with loose fibrils to a compacted structure with collapsed fibrils and collapsed lamellae. Carlsson (53) reported a slight decrease in water retention values for fibers pressed to 65% solids versus 45% solids, indicating some hornification. Carlsson et al. (22) also noted that sheets which had been previously compressed to a high solids content had a higher permeability. The authors imply that it is the compression and not the partial drying of fibers that cause this effect. For the range of compression applied to sheets in this study, we have not observed changes in the permeability-porosity relationship due to compression as long as the sheet stayed saturated (i.e., water was added during expansion).

Recycled fibers. Figure 17 compares the effect of recycling (drying and reslushing) with transverse permeability changes caused by pressing and drying of a sheet. A sheet made from the recycled fibers shows about the same permeability as a sheet made from never-dried fibers which has been pressed to 50% solids prior to resaturation. The recycled fibers are expected to have a lower permeability than a sheet which was completely dried because the process of recycling results in some fiber breakage, producing more fines. Furthermore, the enlarged interfiber pores caused by drying in a sheet are locked in place when the sheet is resaturated, whereas when the sheet is disintegrated to form a new sheet, the fibers are freed to possibly form a relatively tighter structure.

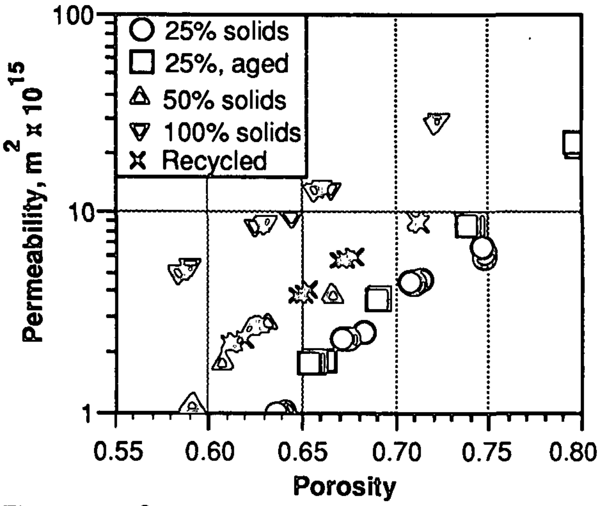

Figure 17. Comparison of permeability in a sheet of recycled fibers with partially dried sheets. Sheets are 135 gsm bleached softwood kraft, initially 715 CSF.

Fines Content

Fines are known to have a significant effect on sheet permeability. This is demonstrated in Figure 18, where we compare permeability in sheets from classified and unclassified pulp. An increase in permeability by a factor of 10 was caused by removal of fines. A Bauer-McNett classifier was used.

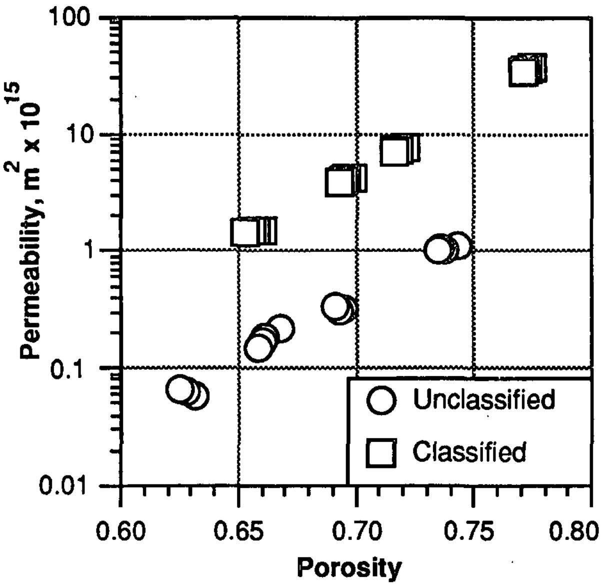

Figure 18. Effect of classification on permeability in 135 gsm sheets of bleached softwood, 654 CSF.

Basis Weight Variation

As noted above, Ellis (23) reported that low-basis weight sheets tended to have higher permeabilities than heavier sheets formed from the same pulp. A similar effect was observed in this study for transverse permeability. Figure 19 shows data for several basis weights of bleached softwo od pulp. The lightest sheet, 135 gsm, has a much higher permeability than the other sheets. This effect was consistently observed in this study. For example, Figure 20 shows the same trend in hardwood fibers.

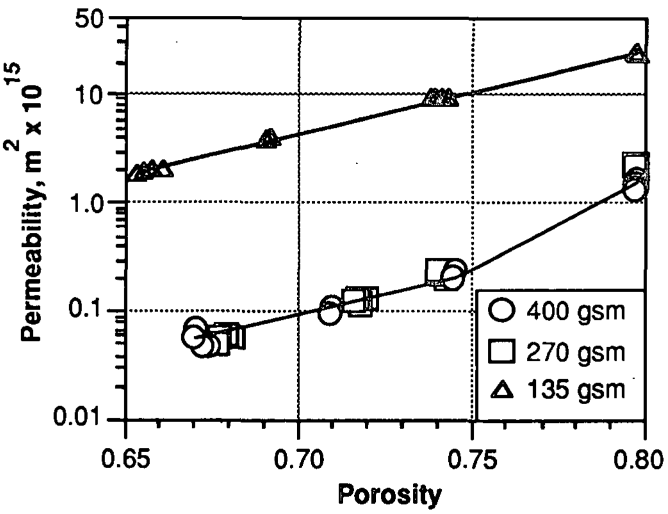

Figure 19. Basis weight effect in bleached softwood sheets.

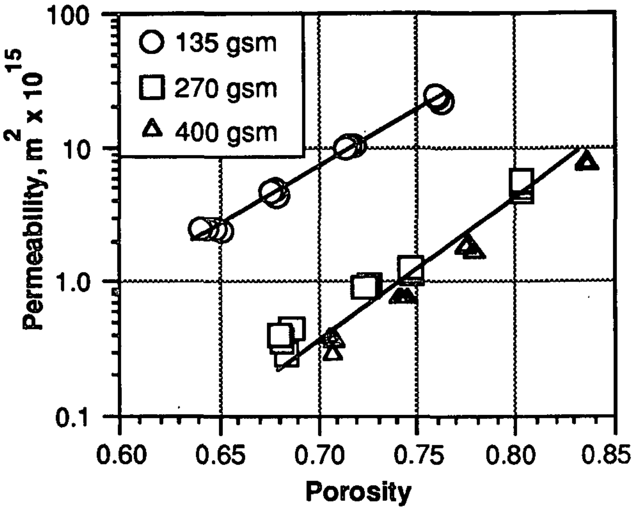

Figure 20. Basis weight effect in bleached hardwood sheets, CSF 567.

To explain the basis weight effect, it was hypothesized that fines distribution may play a role. According to this hypothesis, fines in heavier sheets may accumulate near the flow-exiting side of the sheet during handsheet formation, creating a low-permeability zone that reduced the apparent permeability of the sheet. In lightweight sheets, however, the smaller quantity of fines might not be sufficient to create a low-permeability layer. This hypothesis was rejected, however, after testing for basis-weight effects in classified pulp. Figure 21 shows the same basis-weight effect in classified bleached softwood pulp.

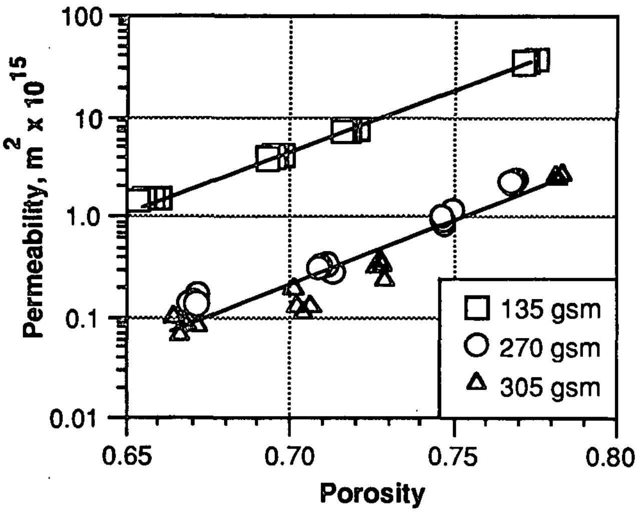

Figure 21. Effect of basis weight for sheets of classified bleached softwood pulp, 654 CSF.

Ellis had hypothesized that the basis-weight effect was due to experimental artifacts caused by the interaction of his sheets with the rough porous surface that supported the sheets during permeability measurement. In our experiments, the smoothness of the felts with respect to the sheet seemed easily sufficient to prevent such an artifact. It appeared that the high permeability was real.

A possible explanation for the effect came during examination of micrographs showing the structure of the sheets. SEM's of the sheets from Figure 19, 135, 270, and 400 gsm bleached softwood, respectively, are presented in Figures 22-25. SEM's of two sheets in Figure 20, the 135 and 270 gsm bleached hardwood, are also shown in Figures 26 and 27. The key feature is the presence of occasional "macropores" in the sheets (esp. Figures 24 and 27) which are almost on the order of the thickness of 135 gsm sheets. The macropores may represent boundaries between flocs or aggregates that occurred during formation. Handsheet formation employs a low-consistency stock to prevent significant flocculation, so floc formation in the suspension may not be the proper explanation. The macropores could be due to sheet disruption by the flow during formation or by couching and pressing of the sheet. In any case, there appear to be macropores in the sheets with a particular length scale. This length scale approaches the thickness of the lightweight sheets but is less than the thickness of the heavier sheets. As a result, these pores could conduct a significant amount of water through a light sheet, where they may nearly pass from one end of the sheet to the other. In heavier sheets, however, these random, large pores do not transverse the majority of the sheet and thus are "averaged out" with the rest of the small pores in the sheet, creating an average permeability that no longer changes much with increasing thickness.

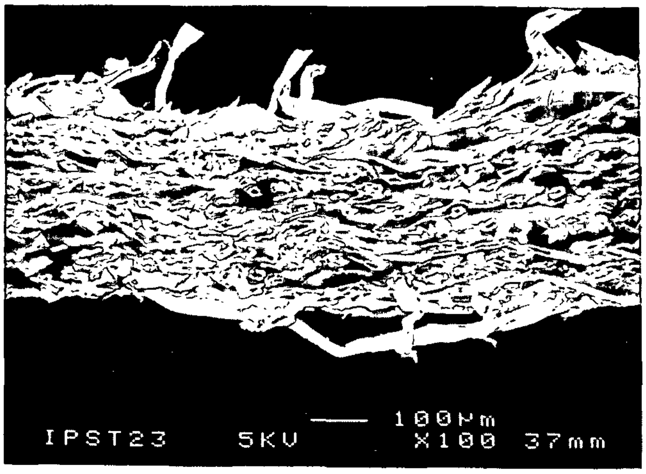

Figure 22. SEM cross-section of a 135 gsm bleached softwood sheet.

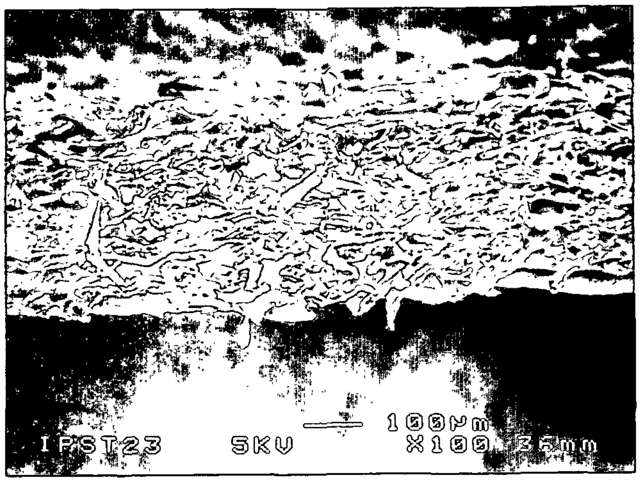

Figure 23. SEM cross-section of a 135 gsm bleached softwood sheet.

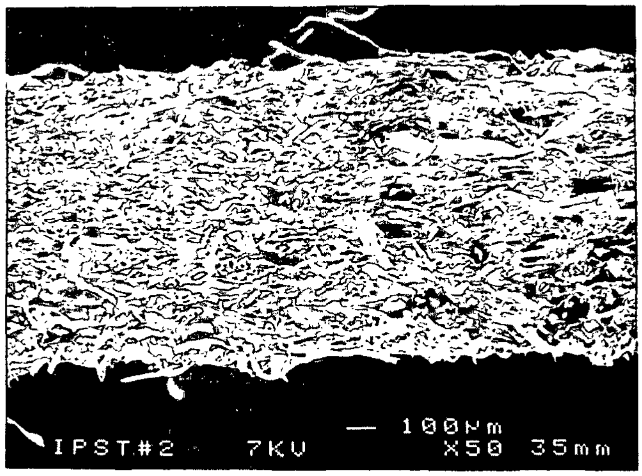

Figure 24. SEM cross-section of a 270 gsm bleached softwood sheet.

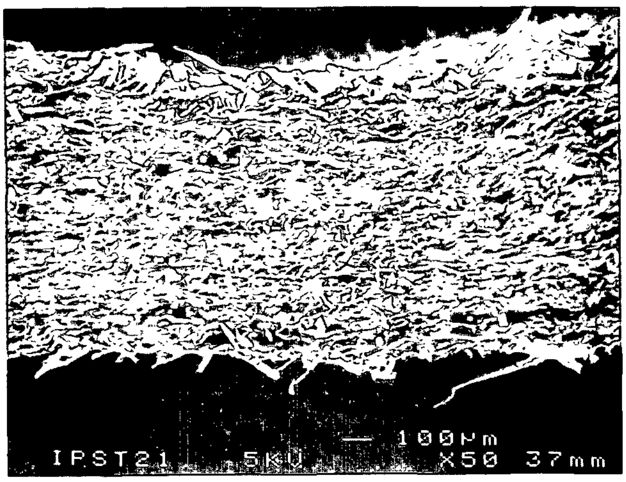

Figure 25. SEM cross-section of a 400 gsm bleached softwood sheet.

Figure 26. SEM cross-section of a 135 gsm bleached hardwood sheet.

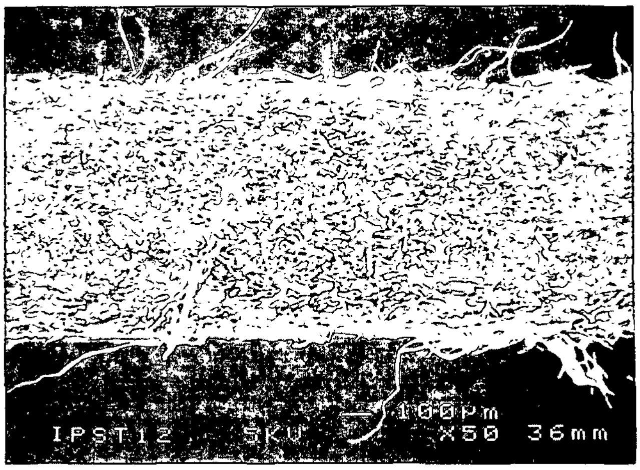

Figure 27. SEM cross-section of a 270 gsm bleached hardwood sheet.

Gren and Hedström (54) also note that nonuniform formation can cause an increase in measured permeability. Intrinsic nonuniformities in paper will thus cause an increased permeability until the sheet is thick enough for the nonuniformities to become small compared to the sheet thickness.

Further insight into the relation between basis weight and permeability comes from a study of air flow in paper by Knauf (55). Using a Gurley porosity tester, Darcian permeability to air in 60 gsm sheets was found to be significantly greater than in 200 gsm sheets. Effects due to surface roughness cannot explain this phenomenon.

A basis-weight effect was not seen in our lateral permeability measurements. In these tests, the flow path is about 3.7 cm through the plane of the paper, and the effects of random macropores are averaged out. However, if the measurement had been made using a much shorter flow path, still higher permeability values for in-plane flow may have been seen.

REPRODUCIBILITY

A variety of factors may affect the reliability of these results. We therefore examined reproducibility and possible experimental artifacts.

Testing for Artifacts

Inertial effects. Darcy's law is not valid when inertial effects become important in a porous medium. At high fluid velocities, the relationship between pressure drop and velocity becomes quadratic, not linear. We tested for inertial effects by measuring the apparent Darcian permeability in a sheet subject to three different pressure drops, with the maximum pressure drop well outside the range used in this study. All three data sets essentially fell on the same line, as shown in Figure 28, indicating that Darcy's law applied.

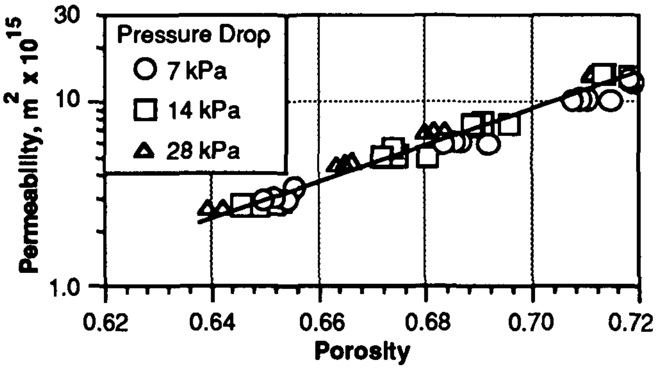

Figure 28. Measurements at different pressure drops to test for inertial effects. Sheet was bleached hardwood, 135 gsm, CSF 653.

Aeration. Another artifact which could be important relates to the effect of air bubbles on measured permeability. Some authors have suggested that careful deaeration of water and sheets is needed, otherwise air bubbles in the sheet could substantially reduce the measured permeability (22). In our testing, we kept the sheet saturated from the point of formation on to prevent intrusion of significant air, and generally used deaerated water. However, we wished to test what affect air bubble formation might have, for the use of pressurized air to pressurize our flow reservoir meant that the air content of the water would increase with time, possibly leading to artificial reduction in permeability during a run. However, when we measured transverse permeability using heavily aerated water, we could find no evidence of a permeability decrease due to air. In previous work we also found no evidence that deaeration of a saturated sheet had an affect on permeability. This is shown in

Figure 29, where we compare lateral permeability measurements in four sheets of West Coast unbleached sulfite pulp, two of which had been deaerated for about several hours under vacuum before making the measurement. At least for the procedures and samples of this study, permeability reduction due to air is not an issue.

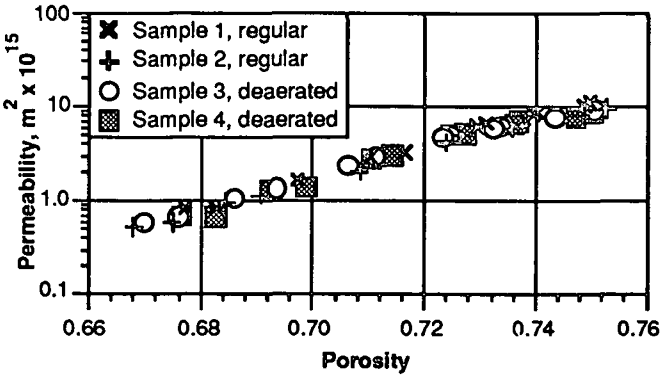

Figure 29. Effect of sheet deaeration on lateral permeability measurements of 200-gsm sheets of West Coast sulfite pulp.

Pulp storage time. We examined the effect of storage on the permeability of the pulp. The pulp was preserved with formaldehyde. After five weeks of cold storage, we could not detect a clear change in permeability for the softwood. The hardwood pulp showed some signs of microbial degradation, but a clear change in permeability was not detected.

Wire effect. The mesh size of the wire used in British handsheet mold was varied between 100 and 150 mesh. No effect of the wire could be detected between samples.

Reproducibility

Because of intrinsic nonuniformities and natural variation in sheet formation, as well as experimental error, measured permeability is subject to variance between samples and within a sample. For example, Figure 30 shows scatter between four data sets consisting of two separate 270 gsm sheets each tested twice. In addition to a difference between the two sheets, the replicate measurements on each sheet give slightly different results.

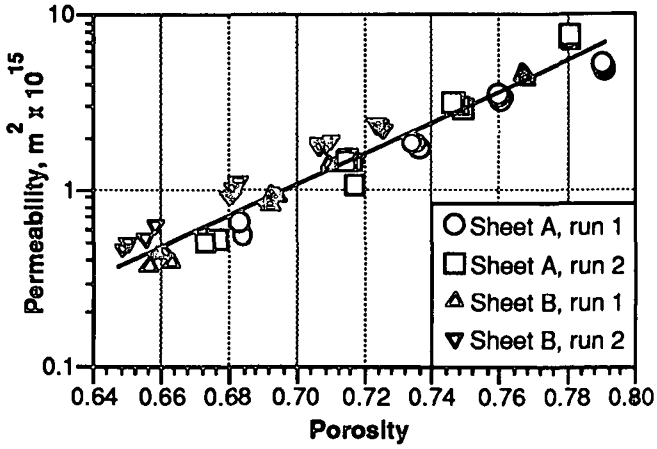

Figure 30. Reproducibility for 270 gsm sheets of unrefined, stored bleached hardwood.

Low basis weight sheets (135 gsm) were subject to additional scatter between samples, possibly due to the randomness of nonuniformities (macropores) which inflated sheet permeability, as discussed above. Figure 31 shows four runs for two samples of 135 gsm hardwood.

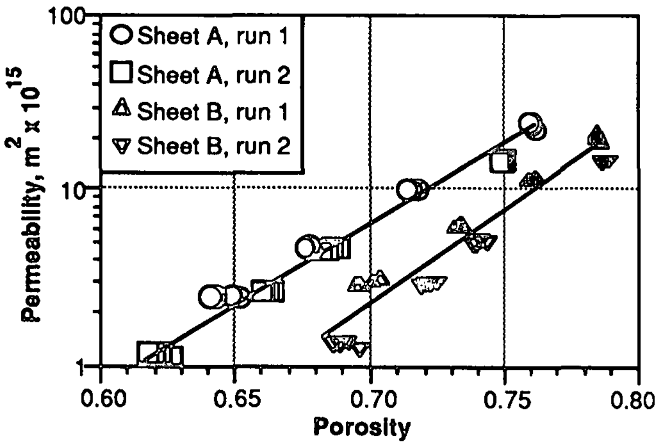

Figure 31. Reproducibility for 135 gsm sheets of unrefined, stored bleached hardwood.

One of the worst cases of scatter is shown in Figure 32, where we tested the heaviest sheets (400 gsm) made from PFI-refined, aged hardwood pulp. This pulp, having been subject to some microbial degradation and having been additionally refined in a PFI-mill, was extremely weak. The thick 400-gsm mat tended to ooze radially outward when compressed, and the sheet was easily disrupted. As a result, replicate measurements posed serious difficulties. Without refining, the fibers were somewhat stronger and seemed to yield less scatter, as shown in Figure 33.

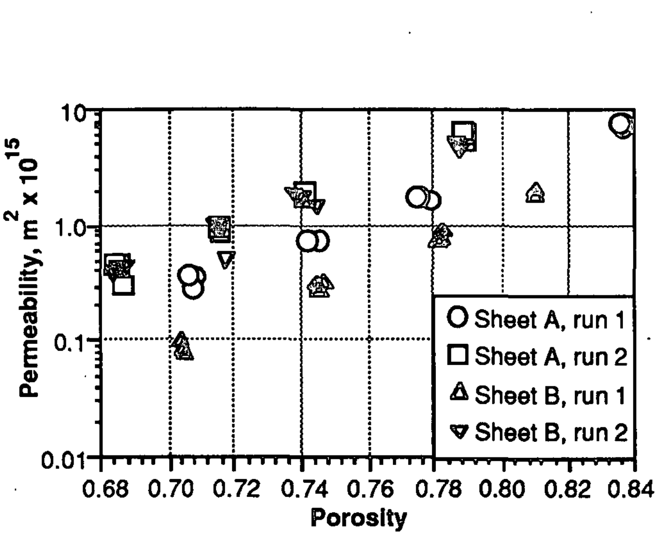

Figure 32. Large scatter in 400 gsm sheets of stored, PFI-refined bleached hardwood.

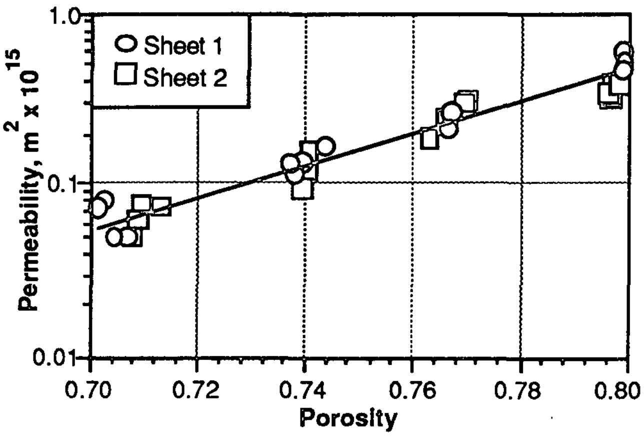

Figure 33. Reproducibility in 400 gsm sheets of *stored, unrefined bleached hardwood.*

DISCUSSION

Nature and Importance of Anisotropy

The levels of anisotropy measured in this study are consistent with the results from the early phases of this study. We have previously reported anisotropy ratios (lateral to transverse permeability) on the order of 10-20 for TMP sheets and 2-5 for unbleached kraft.

The high levels of anisotropy measured in this study and in our previous work are of special importance to wet pressing and related water removal processes. The implication is that in-plane flows may be more important than previously realized, for previous analyses have generally been based on the assumption of equal permeability in all directions. Our results, however, show lateral permeability may exceed transverse permeability by an order of magnitude or more.

Roux and Vincent's recent numerical modeling of wet pressing indicated that a 1% loss in outgoing solids might occur in a press if the anisotropy ratio was 5. While the modeling of wet pressing is a formidable task and is subject to many possible errors, this result appears physically reasonable. High in-plane permeability allows some of the water near mid-nip to flow in the plane of the paper instead of all going in the transverse direction to the felt. Water removal is thus reduced by high in-plane permeability.

In-plane water flow will be reduced by increasing nip length, for the increased length scale for in-plane flow means the in-plane pressure gradient is reduced and less flow in the plane can occur. Shoe presses, for example, are likely to have negligible in-plane flows.

Cause of Anisotropy

The anisotropy levels reported here are far beyond what has been predicted based on simple models of flow over aligned cylinders, where a ratio no greater than 2 is expected (e.g., see discussion in [34]). However, these models fail to describe the pore structure of consolidated paper. The flattened, fibrillated fibers in a compressed mat are much unlike an array of uniform cylinders. Theoretical work by Brown (56) for flow through arrays of elliptical fibers indicates that anisotropy values much greater than 2 may occur for fibers with flattened elliptical cross sections (high aspect ratios). This is consistent with the recent work of Hamlen and Scriven (57), who developed a computational model for three-dimensional pore structure and pemeability in a web made of regular, deformable fibers. In one set of predictions, anisotropy ratios greater than 2 occur for high aspect ratio fibers. For example, an aspect ratio of 14 (height-to-width ratio of 0.07) was predicted to have an anisotropy ratio greater than 7 for a high linear fiber density.

In general, the combination of fiber geometry and planar fiber orientation creates an anisotropic flow network. Pores in the z-direction are continually interrupted by the broad projection of flattened fibers. Pores in the plane meander alongside fibers and over or under the thin projections of fibers. The final result is high in-plane permeability and low transverse permeability. The process of sheet formation also creates a pore structure with lower z-directional permeability than a random fiber network because of the "self-healing" effect in which random, open pores accommodate more flow and thus are quickly sealed as more fibers are deposited.

Changing pore structure during compression is likely to affect anisotropy. The change in anisotropy with compression is not yet well understood, although typical data sets in this study suggest a mild decrease in anisotropy with increasing compression (decreasing porosity). Hamlen and Scriven (57) predicted a strong decrease in anisotropy with compression, enough so that transverse permeability could exceed lateral permeability in sufficiently compressed webs. This possibility will be further explored in future work.

Macropores and Basis Weight Variation

Based on measurements and micrographs, macropores between fiber aggregates may contribute substantially to the measured permeability of a sheet. In sheets too thin for these pores to be averaged out, a significant inflation in measured transverse permeability may occur. This effect was not seen in lateral permeability measurements because a long flow path through the plane of the sheet was used.

Lateral permeability may be even higher than we measured for flow processes where the in-plane flow occurs across a small distance. In this case, macropores may then inflate the apparent permeability, as they presumably did in our measurements of transverse permeability in thin sheets. Indeed, in processes such as blade coating, where the in-plane pressure gradient under the blade has a very small length scale, nonuniformities or macropores may play a major role in the penetration of coating into the paper. This is consistent with phenomena observed by Windle et al. (58).

An important implication of this finding is that moderate to low basis weight sheets may need to be treated as heterogeneous media rather than uniform porous media. Analysis of transport phenomena in processes like wet pressing, blade coating, and drying may be incorrect if the assumption of homogeneity is made, as it almost always is. There may be a need to consider complex stochastic transport models, which treat the porous medium as having a statistical distribution of pore sizes.

CONCLUSIONS

Based on the data presented above, the following conclusions are offered:

- In-plane permeability in paper can be higher than the transverse permeability by factors on the order of 2-40.
- For pressing and drying operations, permeability is a more useful measure of water removal behavior than freeness. Both in-plane and transverse permeability may be important in pressing operations.
- Partial water removal through pressing can change the pore structure by decreasing fiber swelling. There is an increase in the permeability of the resaturated sheet.
- Dried and resaturated sheets have higher permeability than sheets formed from dried and reslushed fibers.
- Low basis weight sheets may have higher than expected transverse permeability because of macropores between fiber aggregates, even in sheets formed from low-consistency slurries.
- The presence of heterogeneities such as macropores in paper may invalidate common assumptions used in analyzing transport processes in paper. Stochastic models may be needed in some cases.

Many issues deserve future study in order to better understand the water removal behavior of fibrous webs in real processes. In future work we will seek to firmly establish the change in anisotropy with compression, testing the computational prediction of Hamlen and Scriven (57) that the nature of the anisotropy can reverse at high compressive loads. The effect of chemical additives or filler particles on the anisotropy of fibrous materials is worthy of study. Permeability to two-phase flows in fibrous structures is another important and largely unexplored area. Gas-liquid flows in fibrous media occur in both papermaking and nonwovens applications. In future work we intend to measure the anisotropic relative permeability behavior of fibrous media in water-air and water-steam flows.

ACKNOWLEDGEMENT

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